A competence development framework for learning and teaching system dynamics

Martin F. G. Schaffernicht[a*] and Stefan N. Groesser[b,c]

Abstract

Current teaching and learning of system dynamics are based on materials derived from the expertise of *masters*. However, there is little explicit reference to neither the stages which *beginners* go through to become *proficient* nor what is learned at each of these stages. We argue that this hinders cumulative research and development in teaching and learning strategies. We engaged 15 acknowledged *masters* in the field to take part in a three-round Delphi study to develop an operational representation of the competence development stages and what is learned at each stage. The resulting system dynamics competence framework consists of a qualified, expert-evaluated, empirically based set of seven skills and 265 learning outcomes. The skills provide a common orientation, in the language of current educational research, to facilitate research, course design and certification efforts to ensure quality standards. To conclude, this paper provides avenues for future work.

Syst. Dyn. Rev. **32**, 52–81 (2016)

> One should enter a complex dynamic situation and aspire to […] talk about the issues for 20 minutes without contradicting oneself.
>
> Jay W. Forrester

Introduction

A system dynamicist ought to develop and exploit a simulation model so as to discover the causal structure and policies driving problematic behaviors as well as promising alternative policies (Forrester, 2007, p. 353). Expert system dynamicists have developed a series of best practices that have been systematized by Martinez-Moyano and Richardson (2013). Such practices implicitly assume that individuals know when to do what, how, for how long, whom to involve and what data to gather.

A significant body of materials has been developed by master system dynamicists to facilitate learning and teaching SD (system dynamics).

[a] Facultad de Economía y Negocios, Universidad de Talca, Avenida Lircay s/n, 3460000, Talca, Chile
[b] Strategy and Simulation Lab, Institute of Corporate Development, Bern University of Applied Sciences, Switzerland
[c] Department of Management, University of St. Gallen, Switzerland
* Correspondence to: Martin Schaffernicht, Facultad de Economía y Negocios, Universidad de Talca, Avenida Lircay s/n, 346000 Talca, Chile. E-mail: martin@utalca.cl
Accepted by Laura Black, *Received 19 July 2015*; *Revised 10 June 2016*; *Accepted 11 June 2016*

System Dynamics Review
System Dynamics Review vol 32, No 1 (January/March 2016): 52–81
Published online 25 August 2016 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/sdr.1550

Some have been published as books (e.g. Maani and Cavana, 2007; Morecroft, 2007; Richardson and Pugh, 1981; Sterman, 2000a; Warren, 2008) and others are freely available for self-directed learning; for instance, RoadMaps (Creative Learning Exchange, 2016). Also, educational programs are offered at both undergraduate and graduate levels (see System Dynamics Society, 2016).

Learning and teaching are active areas of research. Some researchers inquire into the adoption of matters related to SD in schools (Kunz *et al.*, 2015). Richardson (2014a, 2014b, 2014c) has converted decades of teaching experience into a canonical teaching sequence, which starts by exploring existing models and then approaches model creation by a process of correcting models. Wijnen *et al.* (2016) have conducted experiments concerning learning from erroneous models. Particular attention has been devoted to the so-called stock-and-flow error, i.e. learning to correctly take into account stock accumulation when one analyzes a dynamic problem (Lakeh and Ghaffarzadegan, 2015; Qia and Gonzalez, 2015).

However, the answers to several questions have remained implicit: precisely *what* is to be learned, *how* these knowledge elements are related to one another, and which ones should be studied first. We call an explicit outline of this a *framework*. Without such a framework, it is difficult for educational researchers to integrate SD into their investigations. Also, developers of new teaching materials and courses do not have an explicit and common orientation concerning what their products should achieve. Moreover, potential learners and users of SD in application fields, e.g. business management, production theory or environmental issues, receive little advice for selecting courses and learning materials appropriate for their respective needs. They do not know what they should expect.

A framework for learning and teaching would lead to advantages for the future development of SD. Previous initiatives to develop frameworks have been undertaken for specific fields such as K-12 education (Waters Foundation, 2012) or practitioner certification. Fisher (2011) lists concepts and practices related to systems thinking and SD that can be introduced at different ages throughout K-12 education. In the area of adult education, a recent proposition by Plate and Monroe (2014) focused on systems thinking. Kubanek (2002) differentiated SD modeling into four skills: systems worldview, computer modeling skills, applications, and communication and leadership. A framework for SD that is not bound to a specific context has not yet been developed, and the following questions still need to be answered: Which skills should be acquired when learning SD? Which development stages can be differentiated? And which learning outcomes are achieved at each development stage?

This paper proposes answers to these questions in the form of a competence framework for learning SD. The framework establishes a terminology informed by educational research, in which the terms competence, skill,

DOI: 10.1002/sdr

development stage and learning outcome have specific meanings (as discussed below).

The framework follows Forrester (2007, p. 355) and intends to cover all relevant aspects of SD, while leaving systems thinking (Forrester, 1994; Schwaninger, 2009) and general problem solving (Eden and Ackermann, 2006; Flood and Jackson, 1991) out of consideration. In doing so, it goes beyond the best practices (Martinez-Moyano and Richardson, 2013) used by previous work reported by Muñoz and Pepper (2016), who propose a set of skills representing the different stages of the model building process and extract learning outcomes from the best practices. Of course, best practices should be learned, but novice learners of SD also have to achieve many intermediate learning outcomes before reaching a development stage where they exercise best practices. Our framework includes these previous and intermediate outcomes (we will frequently use "outcomes" to abbreviate learning outcomes). While Muñoz and Pepper go on to propose activities for learning, teaching, giving feedback and for assessing, our framework concentrates on the learning outcomes.

Our framework consists of seven skills that are learned over four development stages from *beginner* to *proficient*, based on the established Dreyfus and Dreyfus (1980) model. For each skill and each development stage, learning outcomes are defined following Bloom's revised taxonomy (Anderson *et al.*, 2001). The framework also accounts for the increasing dynamic complexity (Groesser, 2012; Senge, 1990; Sterman, 2000a) of the content to be learned.

A Delphi study with 15 SD masters allowed us to identify these skills and outcomes, to classify their respective relevance and to indicate at which development stage the outcomes are best positioned. The framework provides a template that researchers and instructors can use and adapt. Learners can both identify areas of knowledge and expertise already achieved, and they can also map the areas of necessary development.

Our framework facilitates educational research on learning activities and teaching sequences, as well as assessment. In teaching SD, there are several benefits. First, teaching institutions that offer SD can benefit from organizing their design and development of learning activities and materials according to the framework. This reduces the burden of selecting learning outcomes and also facilitates complementarity between the activities and materials. Second, the competence framework facilitates the development of learning activities and materials for self-study efforts. In addition, lecturers in specific content areas, e.g. economics, business management and public policy, are likely to become interested in integrating SD into their research and teaching, since a detailed identification of the learning outcomes and skills helps identify the application problems where SD is particularly useful.

This paper proceeds as follows. In the next section, we provide the conceptual foundations of the competence framework. Thereafter, we introduce our

DOI: 10.1002/sdr

research design. In the results section, we present the results of our Delphi study by providing an overview of all skills, the competence development stages specific to SD as well as the outcomes of each stage. Then we discuss these results. The last section details avenues for future research that have emerged from our framework. The paper provides additional material in an electronic supplement (supporting information).

The conceptual elements of the competence framework

A framework establishes a series of concepts using specific taxonomies and models (Ostrom, 2007). Our proposal employs the concepts competence, skill, learning outcome and development stage. We also use Bloom's revised taxonomy to describe the skills and learning outcomes. Moreover, the framework contains what the educational literature refers to as a stage model of competence development. However, the term *model* has a specific meaning in the field of SD; therefore we try to avoid the term in the framework, although in some places its use is unavoidable. The following subsections introduce the conceptual tools we used to develop our framework: the Dreyfus and Dreyfus model of competence development stages, Bloom's revised taxonomy of cognitive skill and taxonomy of complexity levels.

Competence, skill and learning outcomes

SD has been related to diverse thinking skills (Forrester, 1994; Richmond, 1993, 1994; Sweeney and Sterman, 2000). These are generic life skills (Shavelson, 2010 p. 58) and as such they are context independent. However, as the descriptions of SD by Forrester and the best practices in SD (Martinez-Moyano and Richardson, 2013) show, SD is not a context-free skill but useful in the context of dynamic complexity (e.g. Moxnes, 1998; Senge, 1990; Sterman, 2008). Therefore, it is not a life skill but a "competence" (Koeppen *et al.*, 2008, p. 62). Although there are numerous definitions of what a competence is (e.g. Roegiers, 2007; Sadler, 2013; Tardif, 2004), we use a generally accepted definition for our purposes here (Shavelson, 2010, p. 44):

> Competence (1) is a physical or intellectual ability, skill or both; (2) is a performance capacity to do as well as to know; (3) is carried out under standardized conditions; (4) is judged by some level or standard of performance as … (5) can be improved …

Koeppen *et al.* (2008) state that valid measures of competence require so-called competence models, which firstly represent the internal structure of competences in terms of specific basic skills and abilities, secondly describe different levels of competence with reference to domain-specific performance,

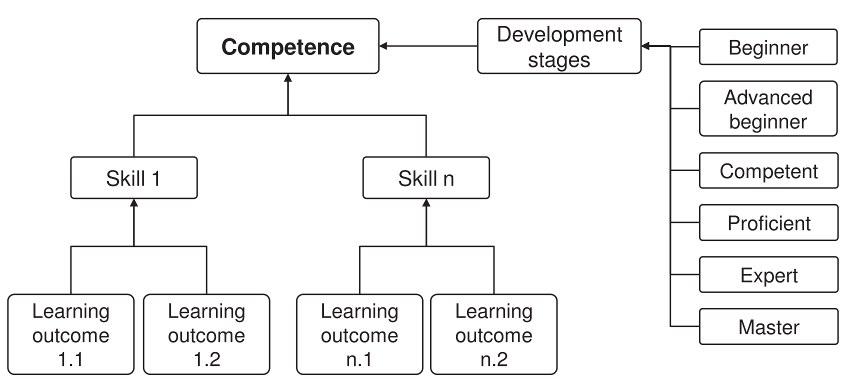
DOI: 10.1002/sdr

and finally account for changes occurring in learning. The internal structure of a competence is made observable by decomposing it into constituent parts called “competency” or “skill”, which are treated as synonymous in the competence literature (Sadler, 2013, p. 15). We use the term “skill”, which is in general used in the SD literature (e.g. Muñoz and Pepper, 2016). Each such skill is then broken down into learning outcomes, which can be directly observed for assessment (Tardif, 2004). These outcomes have been formulated using the well-established Bloom taxonomy as described in the following subsection. Rather than clinging to Bloom’s original term of “learning objectives”, we use current nomenclature from the most recent discussion in the education realm (European Union, 2011). Figure 1 represents the conceptual components and their interrelationships.

Bloom’s taxonomy of learning objectives

To organize the skills and outcomes in a way compatible with the terminology used in the field of education, we have used Bloom’s revised taxonomy (Anderson *et al.*, 2001). Bloom *et al.* (1956) provide a guiding taxonomy of cognitive, affective and psychomotor educational objectives. The cognitive taxonomy proposes six cognitive processes, representing “skill levels” of increasing complexity, progressing from simple ones—remembering, understanding and applying: levels 1–3—to more complex ones, which are composed of many interconnected parts (analyzing, evaluating and creating; levels 4–6). Since they are processes, verbs have been chosen to describe them. The higher-level processes (4–6) are based on lower levels (1–3), but according to Anderson *et al.*’s revised version (2001) there are no systematic level differences between them (for details and a table of verbs used in the respective SD skills, refer to Appendix 1 in the electronic supplement). Each skill level consists of a number of

Fig. 1. A competence is composed of skills, which are themselves composed of learning outcomes. Competence develops over a sequence of stages



DOI: 10.1002/sdr

skills, which are expressed as verbs and exemplify what a learner should acquire and be able to carry out.

Competence development stages

Since skills are acquired over time, our framework includes a sequence of development stages. Owing to the absence of an empirically tested set of development stages for SD (Tardif, 2004), we use a competence stage model that is widely known in the field of management and commonly referred to as the Dreyfus–Dreyfus model (Dreyfus and Dreyfus, 1980; Eraut, 2000). Even though it has been criticized, it is still highly accepted amongst researchers (Dall'Alba and Sandberg, 2006). According to this model, a *beginner* (B) proceeds to *advanced beginner* (AB), to *competent* (C), to *proficient* (P), to *expert* (E) to become a *master* (M).

The evolution from *beginner* to *proficient* consists of assimilating new concepts and skills; in the later stages, personal experience transforms the declarative knowledge and rules into fluid knowing-in-action (Neuweg, 1999; Polanyi, 1983). The difference between *proficient* and *expert* cannot be expressed in terms of skills; rather, it is grounded in the number of years of deliberate practice and the number of projects, cases or situations resolved (Ericsson *et al.*, 1993, 2007). Mastery is an even higher degree of maturation. When an *expert* is able to articulate his expertise, can make it understandable for others in different forms and can teach his knowledge to others, then he has become a *master* (refer to Appendix 2 in the electronic supplement for more details). Therefore, educational programs provide learning opportunities up to the stage of *proficient*. There are no formal courses for becoming an *expert* or a *master*. One aim of this paper is to make advances in the realm of teaching SD in educational institutions. Hence the paper focuses on the stages from *beginner* to *proficient*.

Complexity levels

In SD, simple things are learned before more complex things. This statement holds for *what* is learned and *how* it is learned. Referring to the *how*, Richardson's "canonical" sequence starts with exploring existing models—which is supposed to be relatively simple—and moves on to ever more complex activities, eventually creating a model. As for *what* is learned, widely used textbooks (Sterman, 2000a; Morecroft, 2007) start with relatively simple models and progress towards more complex ones. The same progression can be observed in the user manuals of leading software packages (for details refer to Appendix 3 in the electronic supplement). Since our framework concentrates on *what* is learned, it follows that learners of SD ought to reach their learning outcomes over a range of

DOI: 10.1002/sdr

problem situations (models) with increasing complexity. Furthermore, given that the framework focuses on the development stages from *beginner* to *proficient*, it needs to represent different levels of complexity of the problems which are modeled by learners.

Something is complex when it is "composed of many interconnected parts" and "so intricate as to be hard to understand or deal with" (Dictionary.com, 2016). The term "complexity" is used in the "complexity sciences", which study "how parts of a system give rise to the collective behaviors of the system, and how the system interacts with its environment" and "how interactions give rise to patterns of behavior" (New England Complex Systems Institute, 2016). The field of SD has acknowledged this as "detail complexity", but it places emphasis on dynamic complexity, i.e. the behavioral consequences of the interactions between elements in a system over time (Richardson, 1999; Senge, 1990; Sterman, 2000b). In organizational research, "relational complexity" is equivalent to detail complexity, and "temporal complexity" to dynamic complexity; interestingly, "manifest complexity" refers to the subjective condition when an individual's cognitive resources make it difficult to understand a situation (Garud *et al.*, 2011). In the remainder of this paper, we use "complexity" as shorthand for "dynamic complexity". Recently, the term "cognitive complexity" has been used by Özgün and Barlas (2015) as equivalent to manifest complexity, and "systemic complexity" represents objective dynamic complexity. They further argue that the complexity of a problem situation is a consequence of three aspects: feedback loops, delays and nonlinearities. Our reading of the aforementioned SD textbooks and software user manuals (e.g. Vensim or iThink/STELLA) suggests that SD *beginners* are confronted with complexity in the form of feedback loops: they are guided through sequences of models starting with single loops and finishing with five to eight relevant loops, which the textbook authors have labeled as such. In the cases of simulation models included in the books' supplementary material, we refer to the number of loops in the "shortest independent loop set" (Oliva, 2004); this is a subset of the total number of feedback loops that consists of the smallest set of loops which include all the links of the model that belong to one or several loops. This avoids counting those loops which are the union of simpler loops in a model. Delays appear as parameters regulating the speed of adjustments in balancing loops; i.e. they appear in loops and sometimes generate oscillations—a complex behavior pattern in feedback loops. Delays are also discussed as standard formulations for information and material delays in chapters of textbooks (Sterman, 2000a, Ch. 11), when the learner has already studied several combinations of feedback loops. Nonlinear relationships represented by table functions are also dealt with in the later chapters in textbooks (Sterman, 2000a, Ch. 14) (refer to Appendix 3 in the electronic supplement for a more detailed discussion regarding the handling of complexity in teaching).

DOI: 10.1002/sdr

A precise and common description of dynamic complexity has not emerged yet and a thorough discussion of this topic is beyond the scope of this paper. However, we choose a practical solution for the purpose of our framework and distinguish between three levels of complexity for the problems modeled and solved by learners during their initial four stages of competence development based on behavior patterns.

A system's behavior can be broken down into atomic patterns (Ford, 1999), fundamental patterns (Sterman, 2000a, p. 108) and combinations thereof. Ford discusses three atomic patterns: linear, exponential and goal-seeking behavior. Models that generate atomic nonlinear patterns involve a reinforcing or balancing feedback loop. Other patterns such as S-shaped growth or overshoot and collapse are combinations of the atomic patterns and involve increasing numbers of positive and negative feedback loops (Morecroft, 2007, Chs 5 and 7; Richardson and Pugh, 1981; Sterman, 2000a, Ch. 8.5). Any realistic situation will feature at least two relevant and interconnected feedback loops, e.g. S-shaped growth dynamics. Therefore, we consider these structures, i.e. models with one or two feedback loops, as the lowest level of complexity. The intermediate level of complexity accounts for problems of growth and decline, e.g. those encountered in business growth, sustainability problems and require at least three to five feedback loops. The highest level of complexity in the framework accounts for problems generated by system structures with six or more relevant feedback loops. Such situations are placed in the most advanced sections of current textbooks (Morecroft, 2007, Ch. 8; Sterman, 2000a, Ch. 20); we see them as a preparation for the transition from teaching problems—which are necessarily small in model size because the "manifest complexity" of a three-loop model can be high for a *beginner*—to real-world problems. Therefore, the proposed three complexity levels account for the content of existing textbooks and other learning materials, but are not meant to describe the complexity of problems studied by professional dynamicists.

Research method

The process leading to the competence framework relied on the personal knowledge and experience of 15 SD masters. We used a Delphi approach (Dalkey, 1969; Dalkey and Helmer, 1963) based on an initial proposal drawn from a review of established textbooks (Morecroft, 2007; Richardson and Pugh, 1981; Sterman, 2000a; Warren, 2008). This proposal contained nine skills and over 140 learning outcomes. We then sampled individuals who have practiced SD for a minimum of 10 years (Ericsson *et al*., 1993, 2007) at an outstanding level and who have accumulated teaching experience of a decade or more. Out of the sample, we invited authors of established literature

DOI: 10.1002/sdr

about teaching SD, who are masters in research on learning with SD, and accomplished professionals.

The Delphi process consisted of three rounds of consultation. In the first round, the masters evaluated the initial list of outcomes with regard to their relevance on a 5-point Likert scale: "1" indicates "not relevant"; "5" is "highly relevant". They indicated when an outcome was not clearly formulated and also enhanced the list with additional ones. For the second round, a revised framework was submitted, and we asked each participant to indicate the appropriate competence development stage for each outcome and, where applicable, for each of the three levels of complexity. We analyzed the responses with respect to how the different outcomes of each skill matched with the development stages. This led to a regrouping of the outcomes into seven skills, which increased the overall consistency and usability of the framework. In the final Delphi round, each outcome was presented under its respective skill, accompanied by the simple average of relevance judgments of all masters and the most frequently mentioned competence development stage from the second round. The masters were asked to evaluate the final presentation of the skills, the outcomes as well as the allocation of each outcome to a development stage, either by expressing their agreement to the previously established values of relevance and development stage or by indicating a different opinion. Over the entire process, the masters' opinions converged and resulted in a consistent competence framework. All outcomes evaluated by the masters with relevance of "5" or greater are now part of the competence framework. The averages of the individual skills range from 5.3 to 5.8 with a low standard deviation.

System dynamics competence framework

The Delphi process resulted in a competence framework with seven SD skills: SD language, dynamic reasoning, model analysis, SD project initialization, model creation, model validation, and policy evaluation and design (Figure 2).

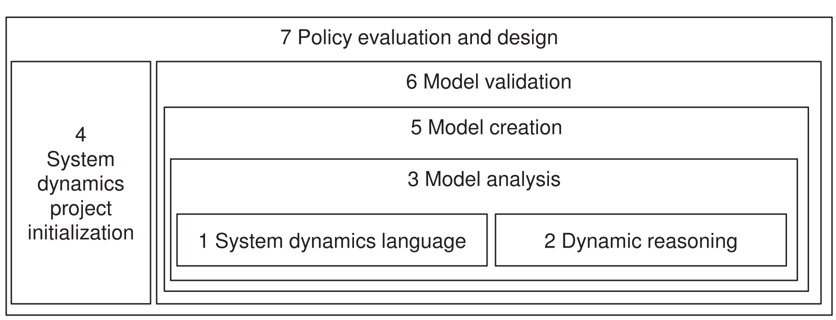


Fig. 2. The system dynamics competence framework consists of seven skills. Higher skills depend on and include lower skills

DOI: 10.1002/sdr

The skills indicate their level according to Bloom's taxonomy: the system's dynamics language (#1) consists of specific concepts and terms that have to be *remembered*; dynamic reasoning (#2) refers to *understanding* the relationship between stocks and flows and the implication of feedback loops. #1 and #2 prepare for model *analysis* (#3), and at the same time both are part of it. Model *creation* (#5) builds on skill #3 to *analyzing* existing models and extends it, just as model *validation* (#6) builds on all the previous skills. Together with project initialization (#4), they prepare for policy *evaluation* and *design* (#7). These seven skills are distinct from each other, but at the same time they belong together: they form a system rather than a sequence, even though simpler skills will be learned before more advanced ones. With respect to project initialization (skill #4), note that the cognitive processes of analyzing and creating or designing overlap. Such overlaps were intended by the authors of the revised taxonomy (Krathwohl, 2002).

Each of the skills is operationalized by a number of learning outcomes. And each outcome is formulated such as to be clearly observable, which makes it operational. Table 1 shows the number of outcomes for each of the seven SD skills.

The leftmost columns of Table 1 show the seven skills, starting with the lowest Bloom level at the bottom and ascending to higher levels. The

Table 1. The seven system dynamics skills and allocated learning outcomes per development stage and complexity level. The development stages are B (beginner), AB (advanced beginner), C (competent) and P (proficient)

Skill	Complexity level (cl)	Competence development stage				No. of learning outcomes
		B	AB	C	P	
	cl3			2	4	6
7 Policy evaluation	cl2		2	4		6
and design	cl1		3	3		6
	cl3			7	2	9
	cl2		7	2		9
6 Model validation	cl1	1	7	1		9
	cl3		1	14	10	25
	cl2		15	10		25
	cl1	1	22	2		25
5 Model creation	n. a.		11	6		17
	cl3			3	6	9
4 System dynamics	cl2		4	5		9
project initialization	cl1		9			9
	cl3			9	4	13
	cl2		10	3		13
	cl1		13			13
3 Model analysis	n.a.		1			1
2 Dynamic reasoning	n.a.	3	9	3		15
1 System dynamics language	n.a.	10	26	10		46
Total numbers of outcomes		15	140	84	26	265

DOI: 10.1002/sdr

outcomes of *system dynamics language* and *system dynamic thinking* skills require only "remembering" (which was formerly referred to as "knowing") and "understanding". The other skills mainly contain modeling related outcomes, which means that the learner has to actually "do" something. Accordingly, skills #3 to #7 are formulated for each of the three complexity levels; "n.a." indicates where the complexity level is not applicable.

The following columns show the development stages and their respective outcomes. Skills #1 and #2 contain many outcomes, but they are concentrated on the early development stages. As one progresses from skill #3 to #7, the majority of outcomes are no longer in stage *advanced beginner* (AB) but in stage *competent* (C). Also, progress from lower to higher complexity levels coincides with advancing from stage AB towards *proficient* (P); however, only few outcomes are achieved in stage P: the *proficient* development stage is not characterized by introducing new outcomes, but by solidifying previously introduced outcomes as personal experience is built up. Accordingly, the numbers of outcomes for each development stage are 15 (B), 140 (AB), 84 (C) and 26 (P).

The 265 outcomes are not equally distributed over the seven skills. Starting with the rows showing the skills *system dynamics language* and *dynamic reasoning*, the outcomes refer to knowing and understanding concepts. Neither skill depends on complexity levels, and therefore the 46 learning outcomes for skill #1 and the 15 learning outcomes for skill #2 (last column) show "n.a." for "not applicable". Beginning with the skill "model analysis", most outcomes take the complexity level into account, and the rightmost column shows the total number of learning outcomes independent of the development stage. According to our masters, *model creation* seems to be of high importance and therefore 75 complexity-dependent, i.e. 25 learning outcomes which are achieved at three complexity levels each, and 17 complexity-independent outcomes are necessary to operationalize it.

Table 2 displays the accumulated percentages of outcomes that are achieved at each of the respective development stages, categorized according to complexity level; outcomes independent from the complexity level are shown as n.a. The outcomes that do not require an action with respect to a more or less complex situation are most significant in the *beginner*

Table 2. Learning outcomes per complexity level over development stage

	Competence development stage			
Complexity level (cl)	B	AB	C	P
cl3	0%	2%	58%	100%
cl2	0%	61%	100%	100%
cl1	3%	90%	100%	100%
Complexity level not applicable (n.a.)	16%	75%	100%	100%

DOI: 10.1002/sdr

stage. The *advanced beginner* ought to have achieved 90 percent of the least complex outcomes and 61 percent of the outcomes at the intermediate complexity. The competent system dynamicist has achieved all the outcomes except 42 percent of the most complex ones, which are acquired at the *proficient* stage.

The progression of outcomes from less complex to more complex situations (models) is what characterizes the development over the different stages, thus underlining the relevance of progressive complexity levels in the framework. We now outline a structured set of learning outcomes for each skill (more details can be found in the electronic supplement).

Skill #1: system dynamics language

SD is a language: it has its own vocabulary with specific meanings attached to the respective terms, leading to a specific worldview and the capability to frame situations in a specific way. Table 3 presents the learning outcomes in

Table 3. Learning outcomes of skill #1: system dynamics language

Learning outcomes	Development stage			
	B	AB	C	P
SD language skill				
Remembers the elements of the modeling process				
Defines the objectives of system dynamics		1		
Lists the phases of the modeling process		1		
Defines the purpose of each phase in the modeling process		1		
Defines the activities of each phase of the modeling process		1		
Defines the methods applied in each phase of the modeling process			1	
Defines the requirements for applying system dynamics			1	
Understands the concepts of system dynamics				
Explains "policy"			1	
Explains "dynamic complexity"		1		
Explains "model purpose"		1		
Explains "reference mode"		1		
Explains "model boundary"		1		
Explains "time horizon"		1		
Explains "dynamic hypothesis"			1	
Explains the types of variables		1		
Explains "units of measure"	1			
Explains "stock"	1			
Explains "flow"	1			
Explains "causality"	1			
Explains "polarity"	1			
Explains "delay"		1		

(Continues)

DOI: 10.1002/sdr

Table 3. (Continued)

Learning outcomes	Development stage			
	B	AB	C	P
Describes the atomic behavior patterns				
Identifies \the atomic behavior patterns in BOT graphs				
Identifies linear behavior (when shown a BOT graph)	1			
Identifies exponential behavior (when shown a BOT graph)	1			
Identifies goal-seeking behavior (when shown a BOT graph)		1		
Describes the atomic behavior patterns in words or as a graph, indicated or drawn				
Describes linear behavior (in words or as a graph, indicated or drawn)	1			
Describes exponential behavior (in words or as a graph, indicated or drawn)	1			
Describes goal-seeking behavior (in words or as a graph, indicated or drawn)		1		
Applies the guidelines of good causal loop diagram development				
Indicates the polarity of causal links		1		
Indicates the polarity of loops		1		
Names the feedback loops		1		
Indicates the important delays in causal links		1		
Names the variables as nouns		1		
Choses an appropriate level of aggregation			1	
Explicates the goals of negative loops		1		
Indicates the relevant feedback loops		1		
Describes standard formulations				
Describes the positive feedback loop	1			
Describes the first order negative feedback loop		1		
Describes the Bass model for S-shaped growth			1	
Describes the loop structure for overshoot and collapse			1	
Describes the second order negative loop capable of oscillation			1	
Describes the material pipeline delay			1	
Describes the material mixer delay			1	
Describes the information delay		1		
Describes the co-flow		1		
Describes the aging chain		1		
Converts diagrams between CLD and SFD				
Constructs a CLD based upon a SFD		1		
Constructs a SFD based upon a CLD		1		

their hierarchical order. The development stage where the majority of the masters interviewed believe an outcome should be achieved is marked with a “1”. For instance, “describes the positive feedback loop” is achieved at the beginner stage (B). More detailed tables with the average relevance score and their standard deviation as well as the development stage associated with the different complexity levels are contained in Appendix 4 of the electronic supplement.

DOI: 10.1002/sdr

Skill #2: dynamic reasoning

Beyond basic language knowledge, it is essential to recognize relevant features of dynamic situations or problems. This implies that one can recognize characteristic behavior shapes, and understand that behavior is driven by causal structures that are feedback loops and stock accumulation. Coming to understand the dynamics also means that one comes to grasp the systemic structure underlying the behaviors. In this sense, "dynamic" also includes "systemic". The learning outcomes are organized as shown in Table 4.

Skill #3: model analysis

The previous two skills are the basic conceptual toolset for SD, but their power unfolds only through the creation and utilization of models.

Table 4. Learning outcomes of skill #2: dynamic reasoning

Learning outcomes	Development stage			
	B	AB	C	P
Dynamic reasoning				
Interprets BOT graphs	1			
Understands stocks and flows				
Describes the difference and the relationship between stock and flow	1			
Defines the rules of graphical integration			1	
Defines the rules of graphical differentiation			1	
Describes a stock's accumulation behavior given the in- and outflows		1		
Describes a flow's behavior given the stock's accumulation behavior		1		
Infers a stock's accumulation behavior given the flows		1		
Infers a flow's behavior given the stock's accumulation behavior		1		
Understands feedback loops in CLDs and SFDs				
Defines the method to detect loops		1		
Infers feedback loops in CLDs and SFDs		1		
Defines the method for detecting loop polarity		1		
Classifies the feedback loops' polarities		1		
Associates changing loop dominance to transitions in atomic behavior patterns			1	
Associates atomic behavior patterns to fundamental feedback structures				
Associates exponential behavior to positive feedback	1			
Associates goal-seeking behavior to negative feedback		1		
Associates fundamental feedback structures to atomic behavior patterns				
Associates positive feedback to exponential behavior	1			
Associates negative feedback to goal-seeking behavior	1			

DOI: 10.1002/sdr

Analyzing an existing model is instructive and being able to do so precedes the ability to create models oneself. Think of how one learns to write; being able to read and understand what one reads is an essential skill for learning how to write.

There are five sets of hierarchically grouped outcomes, which in combination enable individuals to analyze models. Table 5 displays these outcomes. Model analysis is the first skill implying the three complexity levels. Therefore, the corresponding learning outcomes must be achieved three times: once per complexity level. In these cases, the table contains a *cl1* for complexity level 1, *cl2* for complexity level 2 and *cl3* for complexity level 3.

For example, the majority of the masters indicate that "explains CLDs" is achieved by the *advanced beginner* at complexity level 1 (one or two loops),

Table 5. Learning outcomes of skill #3: model analysis

Learning outcomes	Development stage			
	B	AB	C	P
Model analysis				
Analyzes structural diagrams (*with respect to their structure and possible behaviors*)				
Interprets structural diagrams (reconstructs a description of their content)				
Interprets the structure of a CLD (reconstructs a description of the model)		cl1&cl2	cl3	
Interprets the structure of a SFD (reconstructs a description of the model)		cl1&cl2	cl3	
Infers plausible behavior patterns from structural diagrams				
Infers plausible behavior patterns from a CLD		cl1&cl2	cl3	
Infers plausible behavior patterns from a SFD		cl1&cl2	cl3	
Explains CLDs (structure and possible behavior)		cl1	cl2	cl3
Decides when simulation is required to infer the system's behavior		n.a.		
Analyzes SF models using the equations				
Interprets the equations of a SF model		cl1&cl2	cl3	
Attributes which part of structure may be driving specific behaviors		cl1	cl2	cl3
Experiments with simulation models to assess proposed hypotheses		cl1&cl2		cl3
Identifies the relevant feedback loops in a quantitative model		cl1&cl2		cl3
Identifies structure that can be deleted to simplify the model		cl1&cl2		cl3
Explains SF models (structure and behavior)		cl1&cl2	cl3	
Compares SF models				
Explains similarities between SFD models.		cl1&cl2	cl3	
Generalizes: proposes a general existing SFD model for a concrete situation		cl1	cl2	cl3

DOI: 10.1002/sdr

for complexity level 2 (three to five loops) at the *competent* stage and for more complex CLDs at the proficient stage. The table expresses this as *cl1*, *cl2* and *cl3* in the columns of the three concerned development stages. However, it is also possible that certain outcomes are reached for two complexity levels at the same development stage. For instance, the majority of the masters believe that "interprets the structure of a CLD" should be achieved at the stage of *advanced beginner* for CLDs with one to two loops, but also for CLDs with three to five loops. In this case, the column *advanced beginner* has a *cl1* and *cl2*, and *cl3* marked in the column of the *competent* stage.

Note that some learning outcomes do not depend on the complexity level: "decides when simulation is required to infer the system's behavior" has a "1" for the *advanced beginner* stage.

Skill #4: system dynamics project initialization

Some activities that are not part of modeling itself have a decisive influence on the quality of modeling work because they define the purpose and the expectations to be fulfilled and hence the success of a modeling project. Project initialization becomes an important skill for individuals who have already gained basic experience (skills #1 to #3) and now start to undertake their own modeling. Also, skills #1 to #3 are important for doing what these learning outcomes describe. And at the same time skill #4 is fundamental for skill #5 (model creation). Project initialization is therefore highly important, and the corresponding learning outcomes are displayed in Table 6. System dynamics is often applied in projects, therefore learning outcomes referring to project activities are relevant.

Table 6. Learning outcomes of skill #4: SD project initialization

Learning outcomes	Development stage			
	B	AB	C	P
SD project initialization				
Prepares a modeling project				
Establishes the clients of a project		cl1	cl2	cl3
Establishes the symptoms that give rise to the project		cl1&cl2		cl3
Establishes the reference modes		cl1&cl2	cl3	
Establishes if system dynamics is an appropriate methodology		cl1	cl2	cl3
Establishes a problem (*with logical and temporal scope*)				
Establishes desirable and feared futures		cl1&cl2	cl3	
Establishes a preliminary model boundary		cl1	cl2	cl3
Engages clients and other relevant actors		cl1	cl2	cl3
Formulates a conceptual model		cl1&cl2	cl3	
Establishes the purpose of the modeling project		cl1	cl2	cl3

DOI: 10.1002/sdr

Skill #5: model creation

The ability to create a simulation model is at the core of *how* SD is executed and delivered. Given a stated purpose (skill #4), investigating what is relevant in a problem situation, understanding how the elements interact to create the situation under study and identifying how to successfully intervene require the creative and disciplined application of the first three skills. Since computer simulation is necessary, a whole range of technical aspects have to be considered. Accordingly, this skill is made up of a larger number of groups of outcomes, when compared to the other skills, and the outcomes are shown in Table 7.

Table 7. Learning outcomes of skill #5: model creation

Learning outcomes	Development stage			
	B	AB	C	P
Model creation				
Decides the bounds of the model				
Decides the model boundary		cl1, cl2	cl3	
Decides the time horizon		cl1, cl2	cl3	
Develops the representation of variables				
Discovers the variables implied by spoken or written text	cl1	cl2	cl3	
Discovers the variables' proper definitions from first principles deduction		cl1, cl2	cl3	
Classifies the variables by type		cl1, cl2	cl3	
Classifies the variables' units of measure		cl1, cl2	cl3	
Develops the representation of causal relationships in an SD model (diagram and equations)				
Elicits data about the relevant causal structure			n.a.	
Discovers causal links implied by spoken or written text		n.a.		
Discovers the polarity of the causal relation between two variables		n.a.		
Discovers causal links from first principles		n.a.		
Classifies the links' polarities		n.a.		
Discovers delays		n.a.		
Formulates equations				
Formulates equations based on "molecules"		n.a.		
Formulates equations based on standard formulations		n.a.		
Formulates equations from scratch			n.a.	
Discovers the shape of nonlinear causal relations between two variables		n.a.		
Distinguishes between actual and perceived conditions		cl1&cl2	cl3	
Uses simulation to improve understanding				
Uses simulation to reproduce reference modes.		cl1&cl2		cl3
Uses simulation to formulate structure-behavior hypotheses		cl1&cl2		cl3

(Continues)

DOI: 10.1002/sdr

Table 7. (Continued)

Learning outcomes	Development stage			
	B	AB	C	P
Attributes tentatively chunks of model structure to a problem under study		cl1&cl2		
Hypothesizes plausible behaviors of variables in standard formulations		cl1&cl2	cl3	
Experiments with simulation models to assess proposed structure-behavior hypotheses		cl1&cl2	cl3	
Modifies simulation models to assess proposed structure–behavior hypotheses		cl1	cl2&cl3	
Designs policies as part of a simulation model				
Modifies simulation models to incorporate policies		cl1&cl2		
Experiments with simulation models to evaluate proposed policies		cl1&cl2	cl3	
Resolves the modeled problems of reality by using simulation models		cl1&cl2	cl2	cl3
Designs a qualitative model (*CLD or SFD*)				
Uses key agents' mental models for model development		cl1	cl2	cl3
Starts the modeling process from key stocks			n.a.	
Infers key variables that have to be endogenous parts of the model		cl1	cl2	cl3
Attributes variables to reference modes		n.a.		
Assures endogenous orientation			n.a.	
Defines the measurement of each variable			n.a.	
Designs a quantitative SF model (*quantifies the variables*)				
Formulates the simplest possible fragments of structure				
Selects adequate standard formulation where possible		n.a.		
Composes logically coherent equations			n.a.	
Validates the model as part of the modeling process		cl1	cl2	cl3
Simulates after adding one piece of structure		n.a.		
Simplifies the model structure			n.a.	
Modifies the SFD model to achieve validity (validates the SF model)		cl1	cl2	cl3
Modifies the model to test scenarios or candidate policies (exploits the SF model)		cl1	cl2	cl3
Improves the problem situation according to the purpose of the model			cl1&cl2	cl3
Decides when to stop the modeling process			cl1&cl2	cl3
Documents the modeling process		cl1	cl2	cl3

Skill #6: model validation

Validation refers to the activities which assure that a simulation model can be trusted to fulfill its purpose inside known bounds (Groesser and Schwaninger, 2012). This has bee n, and continues to be, an essential aspect of SD work and

DOI: 10.1002/sdr

therefore stands apart from model creation. The skill consists of three groups of outcomes and is shown in Table 8.

Skill #7: policy design and evaluation

The creation of a trustworthy model is the means of SD—the end is an improved understanding and enhanced decision policies. Table 9 displays the corresponding learning outcomes.

Table 8. Learning outcomes of skill #6: model validation

Learning outcomes	Development stage			
	B	AB	C	P
Model validation				
Validates model's structure				
Validates dimensional consistency		cl1&cl2	cl3	
Validates each variable's correspondence to a real entity		cl1&cl2	cl3	
Evaluates a model's membership of a model family			cl1&cl2	cl3
Validates models' behaviors				
Validates the historic fit between the simulation and the reference mode		cl1	cl2	cl3
Tests extreme condition behavior		cl1&cl2	cl3	
Evaluates extreme condition behavior		cl1&cl2	cl3	
Tests the sensitivity of the model with respect to uncertain parameters		cl1&cl2	cl3	
Evaluates the sensitivity of the model with respect to uncertain parameters		cl1&cl2	cl3	
Decides when to stop the validation process	cl1	cl2	cl3	

Table 9. Learning outcomes of skill #7: policy evaluation and design

Learning outcomes	Development stage			
	B	AB	C	P
Policy evaluation and design				
Explains the causal structure of a problem or situation		cl1&cl2	cl3	
Explains how the problem is created by the model structure		cl1&cl2	cl3	
Explains why one policy has high impact while others fail to do so		cl1	cl2	cl3
Explains how established policies are the underlying cause of the problematic behavior				n.a.
Argues in favor of better policies			cl1&cl2	cl3
Communicates effectively with stakeholders about the use of the model			1	

DOI: 10.1002/sdr

Policy analysis and design is the ultimate objective of SD and cannot be reached without a sufficient ability to combine all the previous skills. Beyond being able to perform these activities in isolation, these skills need to be integrated when evaluating and designing policies. This is why skill #7 is the most challenging to achieve. It implies extensive modeling experience, a high level of understanding and the ability to communicate this knowledge effectively to policymakers and problem owners.

Discussion

The framework as orientation

The competence framework consists of seven skills, which have been described by learning outcomes to such a degree that they can be observed for evaluation. It also positions the outcomes at specific competence development stages and thereby enables an evaluator to monitor a learner's progress. Therefore, the framework fulfills the criteria defined for competence models as described by Koeppen *et al*. (2008, p. 62).

The degree of consensus amongst the participating masters of SD is high in general and suggests that the framework covers the relevant capabilities and knowledge of the SD methodology. Most of the outcomes have been evaluated as highly relevant. The only exception is observed for the outcome "*Designs a qualitative model* (*CLD or SFD*)" in skill #5, model creation: the use of qualitative SD is not considered to be the highest relevance by some SD *experts*. Accordingly, the variation in the indicated relevance is higher for outcomes related to qualitative SD. For each outcome, it is clear at which development stage the majority of the *masters* we interviewed believe it should be reached and assessed, and wherever their judgement diverges there is space for flexibility. Thus course designers receive useful orientation for their work.

Courses, study programs, and competence development stages

SD education is obtainable at different institutions that offer courses ranging from short workshops or individual SD courses, to full master programs and up to comprehensive PhD programs dedicated to the methodology. Depending where SD is taught, courses can be either embedded in a specific subject area, e.g. management or engineering subjects, or they can be generic courses on SD. Additionally, courses either aim to train fully fledged modelers or aim to educate users on how to run existing models and interpret them. Our competence framework is a practical to guide potential learners, given the variety of courses available. It can support educators in revising their courses, learning activities and assessments. Time can be used more effectively when deciding what should be taught at which development stage. Also, the

DOI: 10.1002/sdr

framework gives an orientation to individuals interested in learning SD by enrolling in such programs. Notwithstanding these advantages of guiding and orienting, the framework is not a final product but a stepping stone to future research.

Future research avenues

The competence framework is as relevant for research as it is for teaching. In the following, we outline future research avenues: (1) corroborating and consolidating the framework; (2) defining issues of *observation* of learners' performances and *interpretation* for assessment; (3) developing learning activities and teaching sequences based upon the outcomes; (4) exploring possibilities for certification of SD *experts*; (5) investigating mutual links between research on dynamic decision making and teaching; and (6) adapting outcomes to specific application fields (Appendix 5 in the electronic supplement offers additional discussion on some of these topics).

Corroboration and consolidation of the framework

The current framework is a design based on the experience of the *masters* who have contributed to the Delphi process. The practice of using the framework in real teaching settings will solidify it. This solidification is a dynamic process because some aspects may turn out to require adjustments. In particular, it may turn out that certain learning outcomes are less relevant under certain circumstances or that additional outcomes are proposed and confirmed to be highly relevant. It may also become necessary to change the allocation of certain outcomes to a different development stage.

The need for revision and modification can be detected by collecting and analyzing the experiences of researchers and educators using the framework. To assure stability, the framework should not be modified in a continuous manner; rather, after 3 or 4 years of field experience, a participative process of revision would allow us to make informed decisions concerning required adjustments. Improvements to the framework and its learning outcomes are, of course, possible and also expected. One avenue to advance is, for instance, to detail skill #4 (SD Project Initialization) with the work done in the area of group model building (e.g. Andersen, Richardson and Vennix, 1997). Another avenue is to explicate and include further learning outcomes about exploratory model analysis (e.g., Pruyt and Islam, 2015). We are currently working on an interactive database to facilitate the use of the framework and encourage users of the framework to share their experiences. (The database can be found at: www.strategysimulationlab.org/sd-competence).

DOI: 10.1002/sdr

Developing the assessment triangle for teaching system dynamics

The assessment triangle specifies what the competence is, which *observations* are required, and how these data are to be *interpreted* to arrive at justified evaluations concerning the degree of competence of an individual at a given time (Shavelson, 2013). The current SD competence development framework details the first of these three requirements. We invite fellow researchers to corroborate and modify the existing framework to arrive at a strong basis for future work. Then, two additional questions arise: What observations provide sufficient data to evaluate different degrees of SD skills? And how do we interpret the observations to arrive at a thorough evaluation of the skills in the SD competence framework? To find answers to these questions we call for collaboration between educational researchers and system dynamicists to explore "scoring rubrics" (National Research Council, 1996, p. 93). A rubric specifies the performance levels with a standard measure for each outcome (Panadero and Jonsson, 2013).

Sequencing of SD learning activities and course design to improve learning

Once it is defined *what* ought to be learned, the question arises *how* it can be learned or taught best. Then, the challenge is to design and develop learning activities and teaching sequences at the different development stages. A teaching sequence consists of learning activities that lead learners to work towards a specific set of outcomes. A teaching sequence should allow learners to achieve a specified competence development stage with as little time and resources invested as possible. Decades of accumulated and reflected experience are available for this endeavor (Richardson, 2014a, 2014b, 2014c). In general, SD is not practiced in abstract but used in situations belonging to an application domain, such as business administration or public policy. Therefore, it is important to take the previous experience of learners in application domains into account: this is what learners can connect the SD learning outcomes to. Therefore, such personal experience in an application domain is an important factor (Beier and Ackerman, 2005; Schaffernicht and Groesser, 2012).

Usage of the framework to guide certification efforts

Our competence framework can also support steps towards future initiatives aiming to certify learners and practitioners up to the stage of proficiency. Based on our framework, assessments can be developed, and it can be argued that the opportunity to obtain certification will enable self-directed learners and practitioners to signal their level of competence to their clients, employers or even pupils. Since the development stages *expert* and *master* are not dealt with in our proposed framework, it does not suggest any particular form of evaluation for those development stages.

DOI: 10.1002/sdr

Reinforcing the links between research in dynamic decision making and teaching

The framework is useful for systematization of research into learning SD. On one hand, it provides guidance on which outcomes have been addressed by previous research. For example, research on fundamental stock and flow failure (Cronin and Gonzalez, 2007; Cronin *et al.*, 2009; Sterman, 2010) addresses the outcomes dealing with outcome "*Understands stocks and flows*" in skill #2: dynamic reasoning. Another research area—the misperception of feedback—is closely related to skill #2's outcome "*Understands feedback loops in CLDs and SFDs*". Research on the nature of delays (Moxnes, 1998, 2004; Paich and Sterman, 1993) addresses the outcome "*Discovers delays*" (skill #5); and studies on the recognition of feedback loops (Schaffernicht and Groesser, 2011, 2014) address all the outcomes mentioned above. The outcomes referring to understanding stocks and flows as well as feedback loops are anchor points for each of these research areas: any advances in understanding the *misperception of feedback* can directly feed into learning activities built upon the outcomes. In addition, the outcomes of the *dynamic reasoning* skill can be revised in response to new research findings.

Packaging of system dynamics to increase uptake in other fields of research

SD has a long tradition of applications in the fields of management and public policy. In management, besides the general advancement of systems thinking (Atwater *et al.*, 2008), the link between the "resource-based view" in strategy research has been emphasized (Groesser and Jovy, 2016; Kunc and Morecroft, 2010; Rahmandad, 2012, 2015; Rahmandad and Repenning, 2015), and SD has been used to teach strategic reasoning (Gary *et al.*, 2008; Kunc, 2012) and innovation (Milling, 1996; Wunderlich *et al.*, 2014). In public management, applications range from performance management (Bianchi and Montemaggiore, 2008) to specific policy areas like public health (Tebbens and Thompson, 2009), health in general (Abdel-Hamid *et al.*, 2014; Abdel-Hamid, 2002; Paich *et al.*, 2009) and climate change (Booth Sweeney and Sterman, 2005; Sterman and Sweeney, 2007). For instance, the issue of how the public perceives global warming and the accumulation of CO_2 in the atmosphere (Sterman, 2008) is linked to skill #2, dynamic reasoning outcome "*describes a stock's accumulation behavior given the in- and outflows*". To adapt this outcome to the specific field, it can be paraphrased as "*describes the CO_2 stock's accumulation behavior given emissions and absorption*".

Applications in economics are sometimes related to the limits to growth (Randers, 2014), sometimes directly connected to misperceptions of feedback (Kampmann and Sterman, 2014) and sometimes they discuss the methodological issues between the disciplines (Saeed, 2014). In general theories of policy process (Anderies and Janssen, 2013), the recognition of feedback loops as a

DOI: 10.1002/sdr

basic component opens the door for SD. If strategic and other resources for company development are categorized as "stocks" (Dierickx and Cool, 1989; Warren, 2008), the above-mentioned outcome would be adjusted to "*describes the production capacity's accumulation behavior given the investment and depreciation flows*". In a similar way, sources of competitive advantage such as network effects, economies of scale, learning curves, standard formation or the accumulation of complementary assets (Mass and Berkson, 1995; Oliva *et al.*, 2003; Sterman *et al.*, 2007) become "reinforcing feedback loops". Such adaptations clearly show the added value of SD to lectures in strategy or public policy, and at the same time reveal where SD fits into other existing courses.

Conclusion

The work reported in this paper provides the first explicit and operational competence development framework for SD. It consists of seven skills that comprise 265 learning outcomes. The process of learning is organized into four successive competence development stages—*beginner*, *advanced beginner*, *competent* and *proficient*—as described in the Dreyfus competence model. The outcomes have been formulated using Bloom's taxonomy. In a three-round Delphi process, 15 SD *masters* have helped to assure that all the relevant outcomes—and only the relevant ones—are included, and that these outcomes are allocated to the most appropriate stages of the learning process. The high degree of convergence with respect to the skills and the competence development stages suggests that the framework is reliable and useful, albeit certainly open to improvements and extensions.

In particular, the use of three levels of complexity and their respective definitions is a proposal based on practical considerations. In our opinion, SD does not yet have an operational and conceptually thorough definition of complexity. Such a definition could lead to refinements in the framework. However, discussion of this is beyond the scope of this contribution.

The framework can be used by educational researchers for contributions to the assessment triangle; it becomes easier to design learning activities, teaching sequences and courses leading to the acknowledgment of competence stages that are understandable to the entire SD community—and beyond. The efforts of researchers and lecturers from different places are easier to accumulate over time, and it is to be expected that future advances in the design of learning activities and teaching sequences will further enhance the quality and efficiency of learning SD for research, practice and education. Future work along these lines will allow refinements concerning the learning outcomes associated with the skills.

The framework is one step towards increasing the supply of highly skilled system dynamicists and the pursuit of the quest to integrate the methodology

DOI: 10.1002/sdr

in established professions (Forrester, 2007). Therefore, we close in calling our colleagues in research and education to develop rubrics, grading rules, learning activities and teaching sequences using our SD competence development framework.

Acknowledgements

Our special thanks go to the System Dynamics *masters* who participated in the Delphi study: David Andersen, Bob Cavana, Bob Eberlein, Etienne Rouwette, Diana Fisher, Andreas Groessler, Martin Kunc, Peter Milling, Camilo Olaya, Oleg Pavlov, George Richardson, Markus Schwaninger, Lees Stuntz, Kim Warren and David Wheat. Also we want to thank Laura Black for her excellent editorial guidance in publishing this paper and the anonymous reviewers for providing critical questions. We also express our gratitude to the Bern University of Applied Sciences, Department for Business, Health, and Social Work, Switzerland, for providing the means to publish this article as an open access article.

Biographies

Martin F. G. Schaffernicht is a professor at the Department of Management Informatics of the College of Business Administration of the University of Talca, Chile. He earned his PhD in Management Science from the University of Montpellier, France. His research deals with mental models, learning and simulation modeling in planning and strategy. He teaches system dynamics at the University of Talca and in the European Master in System Dynamics.

Stefan N. Groesser is a professor of Strategic Management, Leader of the Strategy and Simulation Lab (S-Lab), and Deputy-Head of the Institute for Corporate Development at the Bern University of Applied Sciences, Switzerland. In addition, he is a senior researcher in strategic management and system dynamics at the University of St Gallen, Switzerland, and he was a visiting scholar at the System Dynamics Group at MIT Sloan. He received degrees from the University of Stuttgart, Germany, in business administration and economics, and from the University of Bergen, Norway, in system dynamics. He received his PhD in Management from the University of St. Gallen. Stefan's research interests include strategic management, business models, mental models and simulation methodology.

References

Abdel-Hamid TK. 2002. Modeling the dynamics of human energy regulation and its implications for obesity treatment. *System Dynamics Review* **18**(4): 431–471.

DOI: 10.1002/sdr

Abdel-Hamid T, Ankel F, Battle-Fisher M, Gibson B, Gonzalez-Parra G, Jalali M, Kaipainen K, Kalupahana N, et al. 2014. Public and health professionals' misconceptions about the dynamics of body weight gain/loss. *System Dynamics Review* **30**(1–2): 58–74.

Anderies J, Janssen M. 2013. Robustness of social-ecological systems : implications for public policy. *Policy Studies Journal* **41**(3): 513–536.

Andersen DF, Richardson GP, Vennix JAM. 1997. Group Model Building: Adding More Science to the Craft. *System Dynamics Review* **13**(2): 187–201.

Anderson LW, Krathwohl DR, Bloom BS. 2001. A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives. Longman: New York.

Atwater B, Kannan VR, Stephens AA. 2008. Cultivating systemic thinking in the next generation of business leaders. *Academy of Management Learning and Education* **7**(1): 9–15.

Beier ME, Ackerman PL. 2005. Age, ability, and the role of prior knowledge on the acquisition of new domain knowledge: promising results in a real-world learning environment. *Psychology and Aging* **20**(2): 341–355.

Bianchi C, Montemaggiore GB. 2008. Enhancing strategy design and planning in public utilities through "dynamic" balanced scorecards: insights from a project in a city water company. *System Dynamics Review* **24**(2): 175–213.

Bloom BS, Engelhart MD, Furst EJ, Hill WH, Krathwohl DR. 1956. Taxonomy of Educational Objectives: The Classification of Educational Goals Handbook I: Cognitive Domain. David McKay: New York.

Booth Sweeney L, Sterman JD. 2005. Cloudy skies: assessing public understanding of global warming. *System Dynamics Reveiw* **18**(2): 207–240.

Creative Learning Exchange. 2016. Available: www.clexchange.org/curriculum/roadmaps. [28 June 2016].

Cronin MA, Gonzalez C. 2007. Understanding the building blocks of dynamic systems. *System Dynamics Review* **23**(1): 1–17.

Cronin MA, Gonzalez C, Sterman JD. 2009. Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. *Organizational Behavior and Human Decision Processes* **108**(1): 116–130.

Dalkey NC. 1969. The Delphi method: an experimental study of group opinion. *Futures* **1**(5): 408–426.

Dalkey NC, Helmer O. 1963. An experimental application of the Delphi method to the use of experts. *Management Science* **9**(8): 458–467.

Dall'Alba G, Sandberg J. 2006. Unveiling professional development: a critical review of stage models. *Review of Educational Research* **76**(3): 383–412.

Dictionary.com. 2016. Available: dictionary.reference.com [28 June 2016].

Dierickx I, Cool K. 1989. Asset stock accumulation and sustainability of competitive advantage. *Management Science* **35**(12): 1504–1511.

Dreyfus H, Dreyfus S. 1980. A five stage model of the mental activities involved in directed skill acquisition. Report by the Air Force Office of Scientific Research (AFSC), USAF (contract F49620-79-0063). University of California, Berkeley, CA.

Eden C, Ackermann F. 2006. Where next for problem structuring methods? *Journal of the Operational Research Society* **57**(7): 766–768.

Eraut M. 2000. Non-formal learning and tacit knowledge in professional work. *British Journal of Educational Psychology* **70**(2): 113–136.

DOI: 10.1002/sdr

Ericsson KA, Krampe RT, Tesch-Römer C. 1993. The role of deliberate practice in the acquisition of expert performance. *Psychological Review* **100**(3): 363–406.
Ericsson KA, Prietula MJ, Cokely ET. 2007. The making of an expert. *Harvard Business Review* July–August: 1–8.
Union E. 2011. Using Learning Outcomes, European Qualifications Framework Series. Publications Office of the European Union: Luxembourg.
Fisher DM. 2011. "Everybody thinking differently": K–12 is a leverage point. *System Dynamics Review* **27**(4): 394–411.
Flood RL, Jackson MC. 1991. Creative Problem Solving: Total Systems Intervention. Wiley: Chichester.
Ford DN. 1999. A behavioral approach to feedback loop dominance analysis. *System Dynamics Review* **15**(1): 3–36.
Forrester JW. 1994. System dynamics, systems thinking, and soft OR. *System Dynamics Review* **10**(2–3): 245–256.
Forrester JW. 2007. System dynamics: the next fifty years. *System Dynamics Review* **23** (2–3): 359–370.
Garud R, Gehman J, Kumaraswamy A. 2011. Complexity arrangements for sustained innovation: lessons from 3 M Corporation. *Organization Studies* **32**(6): 737–767.
Gary MS, Kunc MH, Morecroft JDW, Rockart SF. 2008. System dynamics and strategy. *System Dynamics Review* **24**(4): 407–429.
Groesser SN. 2012. Co-evolution of Standards in Innovation Systems: The Dynamics of Voluntary and Legal Building Codes. Contributions to Management Science. Springer: Heidelberg.
Groesser SN, Jovy N. 2016. Business model analysis and innovation using computational modeling: a strategy tool for exploration and decision-making. *Journal of Mangement Control* **27**(1): 61–88.
Groesser SN, Schwaninger M. 2012. Contributions to model validation: hierarchy, process, and cessation. *System Dynamics Review* **28**(2): 157–181.
Kampmann CE, Sterman JD. 2014. Do markets mitigate misperceptions of feedback? *System Dynamics Review* **30**(3): 123–160.
Koeppen K, Hartig J, Klieme E, Leutner D. 2008. Current issues in competence modeling and assessment. *Journal of Psychology* **216**(2): 61–73.
Krathwohl DR. 2002. A revision of Bloom's taxonomy: an overview. *Theory Into Practice* **41**(4): 212–264.
Kubanek G. 2002. A system dynamics skills inventory for self taught practitioners: a report for the Policy Council of the System Dynamics Society. Available: http://systemdynamics.org/SDS%20PC%20Web/SDskillinventorymatrix3.htm [28 June 2016].
Kunc M. 2012. Teaching strategic thinking using system dynamics: lessons from a strategic development course. *System Dynamics Review* **28**(1): 28–45.
Kunc MH, Morecroft JDW. 2010. Managerial decision making and firm performance under a resource-based paradigm. *Strategic Management Journal* **31**(11): 1164–1182.
Kunz P, Frischknecht-Tobler U, Bollmann-Zuberbühler B, Groesser SN. 2015. Factors influencing the adoption of systems thinking in primary and secondary schools in Switzerland. *Systems Research and Behavioral Science* DOI:10.1002/sres.2391
Lakeh AB, Ghaffarzadegan N. 2015. Does analytical thinking improve understanding of accumulation? *System Dynamics Review* DOI:10.1002/sdr.1528

DOI: 10.1002/sdr

Maani KE, Cavana RY. 2007. Systems Thinking, System Dynamics: Managing Change and Complexity, **2**. Auckland, New Zealand: Pearson Education.

Martinez-Moyano IJ, Richardson GP. 2013. Best practices in system dynamics modeling. *System Dynamics Review* **29**(2): 102–123.

Mass NJ, Berkson B. 1995. Going slow to go fast. *McKiney Quarterly Autumn* 18–29.

Milling PM. 1996. Modeling innovation processes for decision support and management simulation. *System Dynamics Review* **12**(3): 211–234.

Morecroft JDW. 2007. Strategic Modelling and Business Dynamics: A Feedback Systems Approach. Wiley: Chichester.

Moxnes E. 1998. Not only the tragedy of the Commons: misperceptions of bioeconomics. *Management Science* **44**(9): 1234–1248.

Moxnes E. 2004. Misperceptions of basic dynamics: the case of renewable resource management. *System Dynamics Review* **20**(2): 139–162.

Muñoz A, Pepper M. 2016. Maintaining stock and flow: a constructive alignment approach to training system dynamicists. *System Dynamics Review* **31**(4): 271–283.

Council NR. 1996. National Science Education Standards. National Academy of Sciences: Washington, DC.

Neuweg H. 1999. Könnerschaft und implizites Wissen: Zur lehr-lerntheoretischen Bedeutung der Erkenntnis- und Wissenstheorie Michael Polanyis. Munich: Waxmann.

New England Complex Systems Institute. 2016. Available: necsi.edu/guide [28 June 2016].

Oliva R. 2004. Model structure analysis through graph theory: partition heuristics and feedback structure decomposition. *System Dynamics Review* **20**(4): 313–336.

Oliva R, Sterman JD, Giese M. 2003. Limits to growth in the new economy: exploring the ‘get big fast’ strategy in e-commerce. *System Dynamics Review* **19**(2): 83–117.

Ostrom E. 2007. Institutional rational choice: an assessment of the institutional analysis and development framework. In Theory of the Policy Process, Sabatier PA (ed). Westview Press: Boulder, CO; 21–64.

Özgün O, Barlas Y. 2015. Effects of systemic complexity factors on task difficulty in a stock management game. *System Dynamics Review* **31**(3): 115–146.

Paich M, Sterman JD. 1993. Boom, bust, and failures to learn in experimental markets. *Management Science* **39**(12): 1439–1458.

Paich M, Peck C, Valan J. 2009. Pharmaceutical Product Branding Strategies: Simulating Patient Flow and Portfolio Dynamics, **2**. Informa Healthcare: London.

Panadero E, Jonsson A. 2013. The use of scoring rubrics for formative assessment purposes revisited: a review. *Educational Research Review* **9**: 129–144.

Plate R, Monroe M. 2014. A structure for assessing systems thinking. *The Creative Learning Exchange* **23**(1): 1–3.

Polanyi M. 1983. The Tacit Dimension. University of Chicago Press: Chicago, IL.

Pruyt E, Islam T. 2015. On generating and exploring the behavior space of complex models. *System Dynamics Review* **31**(4): 220–249.

Qia L, Gonzalez C. 2015. Mathematical knowledge is related to understanding stocks and flows: results from two nations. *System Dynamics Review* **31**(3): 97–114.

Rahmandad H. 2012. Impact of growth opportunities and competition on firm-level capability development trade-offs. *Organization Science* **23**(1): 138–154.

Rahmandad H. 2015. Connecting strategy and system dynamics: an example and lessons learned. *System Dynamics Review* **31**(3): 149–172.

DOI: 10.1002/sdr

Rahmandad H, Repenning N. 2015. Capability erosion dynamics. *Strategic Management Journal* **37**(4): 649–672.
Randers J. 2014. A realistic leverage point for one-planet living: more compulsory vacation in the rich world. *System Dynamics Review* **30**(4): 264–282.
Richardson GP. 1999. Feedback Thought in Social Science and Systems Theory. Pegasus Communications: Waltham, MA.
Richardson GP. 2014a. "Model" teaching II: examples for the early stages. *System Dynamics Review* **30**(4): 283–290.
Richardson GP. 2014b. "Model" teaching III: examples for the later stages. *System Dynamics Review* **30**(4): 291–299.
Richardson GP. 2014c. "Model" teaching. *System Dynamics Review* **30**(1–2): 81–88.
Richardson GP, Pugh AL III. 1981. Introduction to System Dynamics Modeling with DYNAMO. Productivity Press: Cambridge, MA.
Richmond BM. 1993. Systems thinking: critical thinking skills for the 1990s and beyond. *System Dynamics Review* **9**(2): 113–133.
Richmond BM. 1994. Systems thinking/system dynamics: let's just get on with it. *System Dynamics Review* **10**(2–3): 135–157.
Roegiers X. 2007. Curricular reforms guide schools: but, where to? Curriculum change and competency-based approaches: a worldwide perspective. *Prospects* **37**(2): 155–186.
Sadler R. 2013. Making competent judgments of competence. In Modeling and Measuring Competencies in Higher Education: Tasks and Challenges, Blömeke S, Zlatkin-Troitschanskaia O, Kuhn C, Fege J (eds). Springer: Frankfurt; 13–28.
Saeed K. 2014. Jay Forrester's operational approach to economics. *System Dynamics Review* **30**(4): 233–261.
Schaffernicht M, Groesser SN. 2011. A comprehensive method for comparing mental models of dynamic systems. *European Journal of Operational Research* **210**(1): 57–67.
Schaffernicht M, Groesser SN. 2012. Learning to think in circles: improving mental models of a dynamic system. In *Proceedings of the 30th International System Dynamics Conference*, St Gallen, Switzerland.
Schaffernicht M, Groesser S. 2014. The SEXTANT software: a tool for automating the comparative analysis of mental models of dynamic systems. *European Journal of Operational Research* **238**(2): 566–578.
Schwaninger M. 2009. System dynamics in the evolution of the systems approach. In Encyclopedia of Complexity and System Science, Meyers R (ed). Springer: Berlin.
Senge PM. 1990. The Fifth Discipline: The Art and Practice of the Learning Organization. Currency & Doubleday: New York.
Shavelson RJ. 2010. On the measurement of competency. *Empirical Research in Vocational Education and Training* **2**(1): 41–63.
Shavelson RJ. 2013. An approach to testing and modeling competence. In Modeling and Measuring Competencies in Higher Education: Tasks and Challenges, Blömeke S, Zlatkin-Troitschanskaia O, Kuhn C, Feje J (eds). Springer: Frankfurt; 29–43.
Sterman JD. 2000a. Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill: Boston, MA.
Sterman JD. 2000b. Learning in and about complex systems. *Reflections* **1**(3): 24–51.
Sterman JD. 2008. Risk communication on climate: mental models and mass balance. *Science* **322**: 532–533.

DOI: 10.1002/sdr

Sterman JD. 2010. Does formal system dynamics training improve people's understanding of accumulation? *System Dynamics Review* **26**(4): 316–334.

Sterman JD, Sweeney LB. 2007. Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter. *Climatic Change* **80**(3–4): 213–238.

Sterman JD, Henderson R, Beinhocker ED, Newman LI. 2007. Getting big too fast: strategic dynamics with increasing returns and bounded rationality. *Management Science* **53**(4): 683–696.

Sweeney LB, Sterman JD. 2000. Bathtub dynamics : initial results of a systems thinking inventory. *System Dynamics Review* **16**(4): 249–286.

System Dynamics Society. 2016. Available: www.systemdynamics.org/courses [28 June 2016].

Tardif J. 2004. A compulsory stage in the planning of competency assessment: identification of progressive and final development indicators. *Pédagogie Collégiale* **18**(1): 1–7.

Tebbens RJD, Thompson KM. 2009. Priority shifting and the dynamics of managing eradicable infectious diseases. *Management Science* **55**(4): 650–663.

Warren K. 2008. Strategic Management Dynamics. Wiley: Chichester.

Waters Foundation. 2012. Web Education. Available: http://www.watersfoundation.org/webed/index.html [28 June 2016].

Wijnen FM, Mulder YG, Alessi SM, Bollen L. 2016. The potential of learning from erroneous models: comparing three types of model instruction. *System Dynamics Review* **31**(4): 250–270.

Wunderlich P, Größler A, Zimmermann N, Vennix JAM. 2014. Managerial influence on the diffusion of innovations within intra-organizational networks. *System Dynamics Review* **30**(3): 161–185.

Supporting information

Additional supporting information may be found in the online version at the publisher's web-site. More information on the most recent version of the skeleton of learning outcomes is available at the following webpage: www.strategysimulationlab.org/sd-competence.

DOI: 10.1002/sdr